Synthesis Design of Bandpass Filter for UWB Applications with Improved Selectivity

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Abstract **─** This paper presents the design of UWB three-pole modified parallel coupled line bandpass filter with improved rejection in the out-of-band frequencies. To achieve the desired UWB requirements using the conventional bandpass filter design, a physical dimension optimization of space-gap between lines, line widths and lengths was applied. An equivalent circuit model is also presented and demonstrates reasonable agreement with simulation results. The optimized filter demonstrates an excellent UWB performance, covering the Federal Communication Commission spectrum bandwidth with low insertion loss and acceptable selectivity. However, this resulting filter structure presents very small gapping between adjacent resonators; that means the filter is unmanufactured. Then an example of an alternative filter structure is finally proposed with null gaping and short-circuited stubs that yields to a fabricated prototype with selectivity improvement. Generally speaking, reasonable agreement is achieved between measurement and simulation results.

Index Terms **─** Bandpass filter, coupling gap, parallel coupled line, rejection band, stub, UWB.

I. INTRODUCTION

The ultra-wideband (UWB) radio technology has been getting increasingly popular due to the high-speed high-data wireless connectivity demand. There is a need to design ultra-wideband bandpass filters covering the whole band permitted by the U.S. Federal Communication Commission (FCC), that extends from 3.1 to 10.6 GHz [1]. The design requirements of these circuits face new challenges among which are included an overall good performance, compact size, wide bandwidth feature and multi-band operation. Various approaches to implement UWB filters can be found through literature [2-4]. Among other microstrip line centered configurations, bandpass filters based on parallel-coupled lines have been widely used in microwave systems, due to their good performance, simple structure, low cost and ease of integration with other devices [5-6].

This paper presents the design of a three-pole parallel coupled lines microstrip bandpass filter (BPF) for UWB applications. The filter design was accomplished in three steps. Firstly, a filter is designed and optimized to cover the FCC band.

The physical parameter dimensions for this initial design are calculated by an ad-hoc tool [6] and then optimized in a second design step to achieve a better UWB performance. However, this resulting filter cannot be fabricated due to the small spacing between adjacent coupled lines.

To solve this limitation, a modified filter structure is proposed in a third design step, by null gapping the space between all the filter parallel resonators, and incorporating short circuited stubs. This final design is manufactured and offers selectivity enhancement, covering the FCC spectrum with lower insertion loss and group velocity flatness, along with elimination of the transmission at low frequency. It also presents a size reduction, and it can be implemented on low cost dielectric substrate of FR4.

II. UWB BANDPASS FILTER: DESIGN AND RESULTS

A. Edge-coupled bandpass filter for UWB applications

According to [7,8,9], the edge-coupled bandpass three-order filter is designed to cover the FCC full band, with center frequency of 6.85 GHz, and passband ripple of 0.5. The filter has been implemented on FR4 substrate with dielectric constant of 4.4 and thickness of 1.6 mm.

As a first step, we define the initial physical dimension

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values of a bandpass filter – space gap (S), width (W) and length (L) of each stage – obtained using the transmission line theory approach as in [6] for a parallel coupled line microstrip (PCLM) design. These dimensions are, in mm: $S_{1,4}=0.1$, $W_{1,4}=0.54$, $L_{1,4}=6.34$, $S_{2,3}$=0.14 mm, $W_{2,3}$=0.46 and $L_{2,3}$=6.36 (see Fig.1).

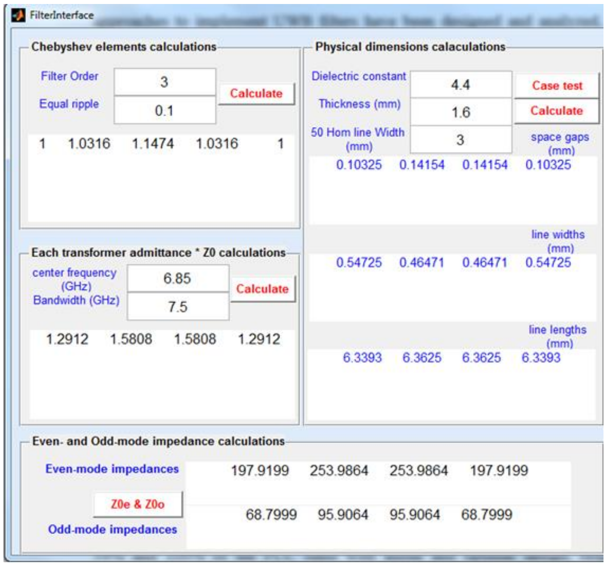


Fig. 1. Parameter calculation tool of the parallel coupled line bandpass filter at 6.85 GHz.

Figure 2 (a) shows the simulated frequency response of the proposed bandpass filter for both initial and optimized designs, using the CST MWs simulator. It can be observed that the initial filter design only covers 85% of the FCC band with low insertion loss and good rejection; however, the optimized filter case presents a UWB response working from 3.1 to 10.6 GHz with low insertion loss and relative good rejection. This improved response is due to the small coupling gap between adjacent filter resonators.

In the next step, we updated the physical dimension values of both filter designs, in mm: $S_{1\text{-}4}=0.05$, $W_{1\text{-}4}=0.75$, $L_{1\text{-}4}=5.6$, $S_{2\text{-}3}=0.075$, $W_{2\text{-}3}=0.55$, $L_{2\text{-}3}=5.95$. The even- and odd-mode characteristic impedances are: $Z_{0e}=1147.33\ \Omega$, $Z_{0o}=37.41\ \Omega$ for sections (1,4) and $Z_{0e}=165.56\ \Omega$, $Z_{0o}=43.57\ \Omega$ for sections (2,3).

To determine the equivalent circuit model of this filter type, the L-C components for the serial and the parallel combination respectively are calculated using the Chebyshev approximation as per (1)-(2):

$$L_s=\frac{FBW.\omega_0}{Z_0.g},\ C_s=\frac{FBW}{Z_0.g.\omega_0}, \tag{1}$$

$$L_p=\frac{FBW.Z_0}{\omega_0.g},\ C_p=\frac{g}{\mathrm{FBW}.Z_0.\omega_0}, \tag{2}$$

where g is the Chebyshev element and FBW is the fractional bandwidth, $FBW=(\omega_1\cdot\omega_2)/\omega_0$, with $\omega_0=(\omega_1\cdot\omega_2)^{0.5}$.

Figure 2 (b) shows the equivalent circuit model response for the optimized UWB PCLM bandpass filer. A good agreement between simulation and equivalent circuit results is clearly observed.

The calculated values of the L-C components for the circuit illustrated in Fig. 2 (b) are: $C_1=C_3=0.625$ pF, $C_2=0.545$ pF, $L_1=L_3=1.225$ nH, $L_2=1.4$ nH.

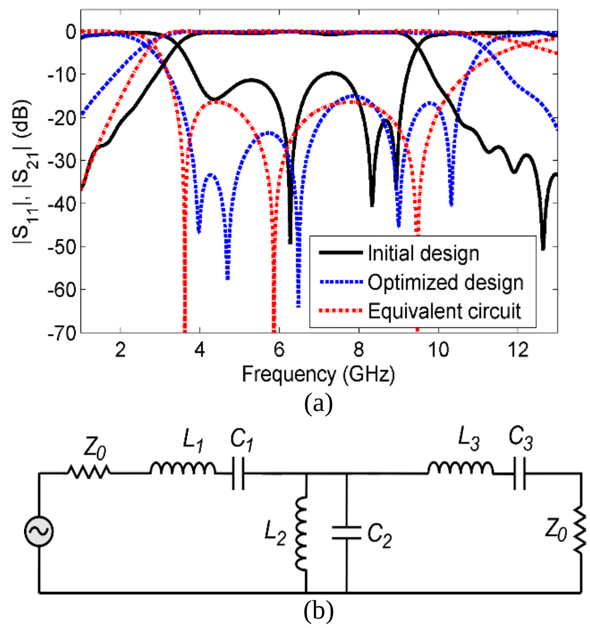


Fig. 2. UWB three-pole PCLM bandpass filter: (a) electrical response for presented cases, and (b) equivalent circuit model.

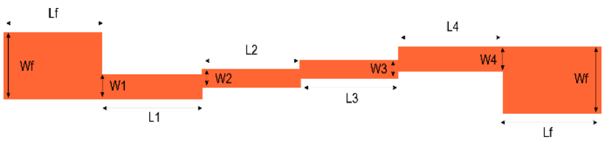
The optimized filter was unmanufactured, due to the resulting very small coupling gap between filter resonators. This geometrical parameter determines the impedance bandwidth of this filter type [6,8]. In the following section, a modified PCLM bandpass filter with null gapping and integrated short-circuited stubs is described.

B. Modified UWB bandpass filter with selectivity enhancement

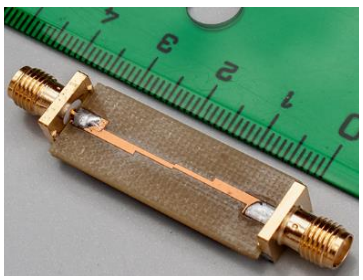
The proposed filter structure consists of setting null gapping between all adjacent PCLM filter resonators and shifting the feed line position to achieve compact filter prototype.

Also, two symmetrical short-circuited stubs are incorporated for improvement of rejection in the out-of-band frequencies and elimination of the transmission at lower frequency band. In Fig. 3, we plotted the geometry of the proposed filter layout without stubs and photograph of the fabricated prototype. The physical dimension values of this filter are, in mm: $W_1 = W_4 = 1.42$, $L_1 = L_4 = 5.8$, $W_2 = W_3 = 0.7$ and $L_2 = L_3 = 6$.

This prototype was measured using a N5222A Agilent Network Analyser. The simulated and measured return loss and insertion of this filter design is plotted in Fig. 4. We note that the fabricated UWB bandpass filter demonstrates a low insertion loss within the FFC band. However, a poor out-of-band rejection performances is seen, due to the small gaps applied between PCLM resonators. Then an enhancement of filter selectivity is necessary.



(a)



(b)

Fig. 3. Modified UWB bandpass filter without stubs: (a) filter layout, and (b) photograph of fabricated prototype.

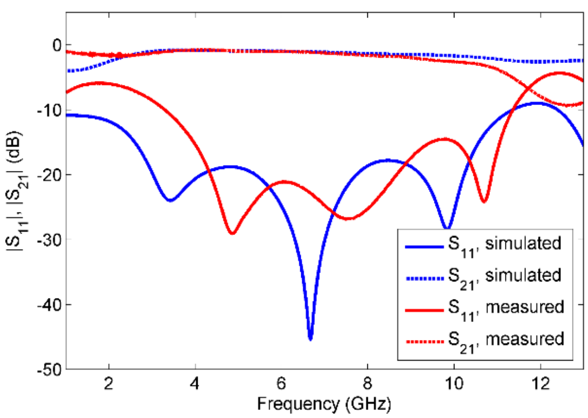


Fig. 4. Electrical response of the modified UWB bandpass filter without stubs.

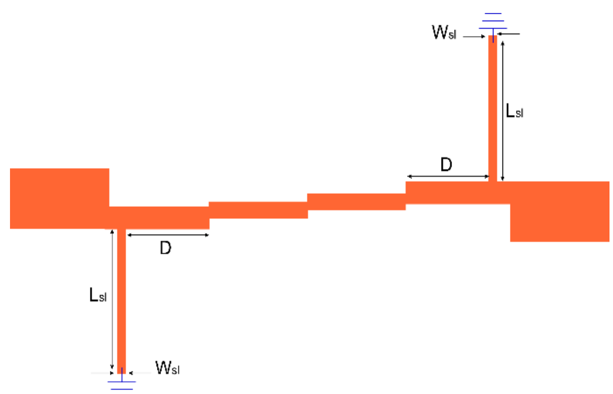
To solve the limitation of poor selectivity, we added two symmetrical short-circuited as shown in Fig. 5 (a), in order to create the desired rejection and eliminate the transmission at low frequency.

The photograph of the fabricated final filter prototype is shown in Fig. 5 (b). For this design, the length and width of the stubs determine the center frequency and bandwidth of the rejected band. Whereas, the rejection level is controlled by the stub positioning parameter, D.

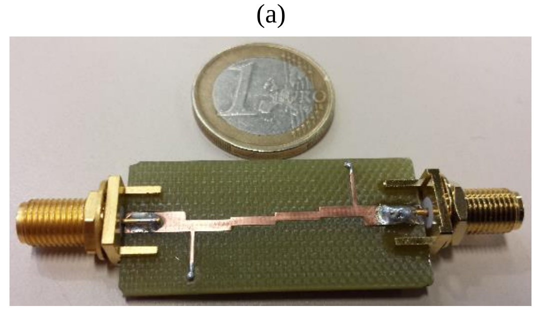
Figure 6 (a) shows the insertion loss of the final modified filter design, with respect to the previous proposed filter cases. The comparison indicates that the modified bandpass filter presents a wider impedance bandwidth, lower insertion loss and improved selectivity. The integrated symmetrical stubs offer a rejection peak at 12.5 GHz (-40 dB). A good agreement is achieved between measurements and simulation.

By comparing to the conventional optimized filter previously presented, the modified filter offers an enhancement in the UWB impedance bandwidth (5%) with improved selectivity. However, it presents a small increase of the insertion loss (about 1.5 dB), due to the integration of the stubs.

Finally, we plotted in Fig. 7, the simulated group delay for the initial, the optimized and the modified filter designs. Within the UWB passband, both of conventional and modified bandpass filters demonstrate flat values (<0.2 ns) of group delay, that meet the requirements established by the FCC regulations for the UWB devices.

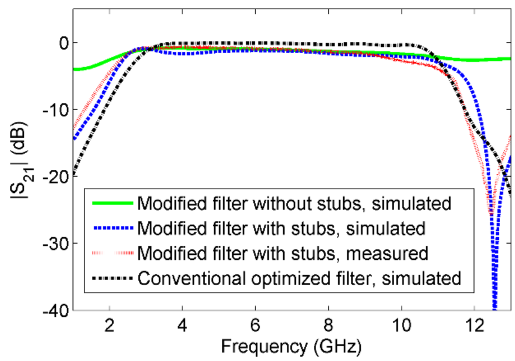


(a)

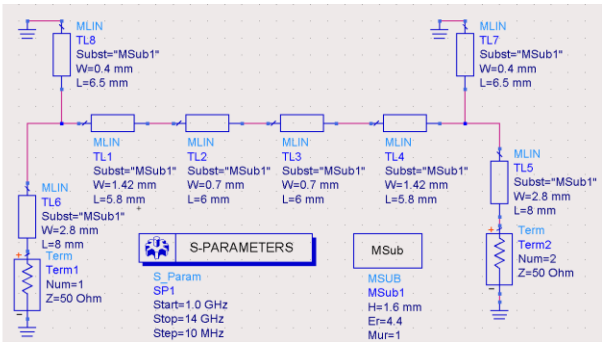


(b)

Fig. 5. Modified UWB bandpass filter with stubs: (a) filter layout, and (b) photograph of fabricated prototype.



(a)



(b)

Fig. 6. (a) Insertion loss of the UWB bandpass filter for all proposed cases. (b) Schematic of distributed elements corresponding to the filter design with stubs.

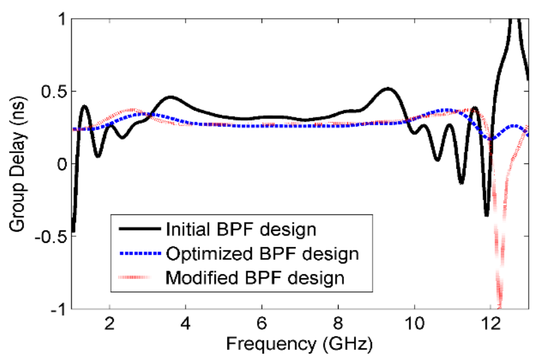


Fig. 7. Parameter calculation tool of the parallel coupled line bandpass filter at 6.85 GHz.

C. Results discussion

Based on the conformal mapping method reported in [10], the even- and odd-mode characteristic impedances of the coupled line depend on the width W and coupling gap S of one stage parallel coupled line. When the dielectric constant ε_r and thickness h of the substrate are known, the impedances Z_{0e} and Z_{0o} can be calculated as a function of the strip line width and coupling gap for each stage of parallel coupled lines of the filter. Then by decreasing the coupling gap S values, the Z_{0e} values increase, Z_{0o} decrease and consequently the bandwidth of the parallel coupled line bandpass filter increases. Detailed analysis and corresponding graphs of the even- and odd-mode impedances are depicted in [12].

Using the closed formulas developed by Hammerstad, Kirschning and Jansen for modelling the frequency-dependency of the even- and odd-mode characteristics of a parallel coupled microstrip line [10,11]. The variation of the static characteristic impedances for even- and odd-modes is calculated easily, as well as the fractional bandwidth (*FBW*) variation of the PCLM filter type. Calculated *FBW*s in (%), for different values of the coupling gaps $S_{1\text{-}4}$ and $S_{2\text{-}3}$ are presented in Table 1. This *FBW* is obtained by determining the ABCD matrix and S-parameters as indicated in [13], based on the design specification presented previously. The three-pole parallel coupled line microstrip bandpass filter implements the FR4 substrate with center frequency of 6.85 GHz and passband ripple of 0.5.

However, this filter configuration with very small coupling gap kept unmanufactured. Then we modified our design by setting null spacing between filter resonators. This resulting structure offers a relative poor selectivity which can be improved using several techniques, such as the short-circuited stubs here described. This latter allows eliminating the lower band frequency transmission.

The resonance frequency of the stub is given by (3):

$$f_{stub} = \frac{c}{2.L.(\varepsilon_{re})^{0.5}}, \qquad (3)$$

where L is the total length of the slot, ε_{re} is the effective dielectric constant and c is the speed of light. The dimensions of the short-circuited stubs here used are: $L_{sl} = 6.5$ mm, $W_{sl} = 0.4$ mm and $D = 4.6$ mm.

Table 1: Variation of the calculated *FBW* in percentage with the small coupling gap values

Gapping ($S_{1\text{-}4}$, $S_{2\text{-}3}$)	Z_{0e} *(1-4, 2-3)*	Z_{0o} *(1-4, 2-3)*	*FBW %*
0.084, 0.709	75.45, 58.52	29.96, 37.74	17.52%
0.03, 0.292	85.61, 66.86	27.47, 33.44	28.32%
0.014, 0.04	100.82, 82.61	26.29, 28.04	43.8%
0.013, 0.015	113.27, 134.1	27.06, 26.29	58.39 %

III. CONCLUSION

In this paper a modified parallel coupled line microstrip bandpass filter for UWB application is presented. Based on a classical design of the parallel coupled line microstrip filters, an UWB bandpass filter is firstly introduced and discussed. Later an optimized design is obtained demonstrating an improved performance with respect to the FCC requirements for UWB devices. A low insertion loss with relative good rejection was obtained within the FCC passband. The equivalent circuit model was also calculated and good agreement is seen with simulation. However, the filter presents very small gap values so demanding a high accuracy in the manufacturing process not achievable for our capabilities.

A limit case is proposed with null gapping to yield a fabricated prototype. The short-circuited stubs are integrated to improve the filter selectivity and eliminate the transmission at low frequency. Measurements results demonstrate the validity of the design method proposed in this paper, achieving an improved performance in terms of UWB bandwidth, low insertion loss and good rejection band without increasing the complexity of the filter structure.

The proposed technique is a good candidate for UWB bandpass filter design, and it can be generally applied to obtain UWB bandpass filters for any specifications.

This work can be extended to achieve a wider rejection in the out-of-band frequencies regardless the used selectivity enhancement technique. As an example, an array of stubs with multiple close resonances.

As set-off, the filter width dimension has grown, and as possible solution to this disadvantage we propose the design of the stub in meander shape. A solution as replacing stubs by stub-slots in the input feedline would affect the S_{21} parameter introducing a larger insertion loss. Despite the disadvantage of the increasing width dimension, the short-circuited stub is a solution valid to jointly achieve an improved selectivity and the elimination of the low-frequency transmission.

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